NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

DESIGN AND VALIDATION OF IMPROVED DYNAMIC CYLINDER PRESSURE MEASUREMENT FOR A DIESEL ENGINE

by

Michael R. Luebkert

September 2005

Thesis Advisor: Knox T. Millsaps, Jr.

Approved for public release; distribution is unlimited

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*

1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** September 2005	**3. REPORT TYPE AND DATES COVERED** Master's Thesis

4. TITLE AND SUBTITLE: Design and Validation of Improved Dynamic Cylinder Pressure Measurement for a Diesel Engine	**5. FUNDING NUMBERS**
6. AUTHOR(S) Luebkert, Michael R.	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000	**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A	**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution unlimited.	**12b. DISTRIBUTION CODE**

13. ABSTRACT (maximum 200 words)

An existing encoder system was analyzed to determine why the system had failed. This encoder system was found to have slipped off the crankshaft, resulting in the need for a new encoder mount system. A new encoder mount was designed and installed on a Detroit Diesel 3-53 engine. The encoder mount was designed to ensure positive contact with the crankshaft while not allowing the mechanism to have the same type of failure that was determined. During the validation of the encoder, the push rod connected to the fuel injector rocker arm failed, preventing further validation of the system. The failure of the push rods is described.

14. SUBJECT TERMS Diesel, Diesel engine, encoder, encoder mount, optical encoder, push rod	**15. NUMBER OF PAGES** 49
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	**18. SECURITY CLASSIFICATION OF THIS PAGE**	**19. SECURITY CLASSIFICATION OF ABSTRACT**	**20. LIMITATION OF ABSTRACT**
Unclassified	Unclassified	Unclassified	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

THIS PAGE INTENTIONALLY LEFT BLANK

Approved for public release; distribution is unlimited

DESIGN AND VALIDATION OF IMPROVED DYNAMIC CYLINDER PRESSURE MEASUREMENT FOR A DIESEL ENGINE

Michael R. Luebkert
Ensign, United States Navy
B.S., United States Naval Academy, 2004

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
September 2005

Author: Michael R. Luebkert

Approved by: Knox T. Millsaps, Jr.
Thesis Advisor

Anthony J. Healey
Chairman, Department of Mechanical Engineering

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

An existing encoder system was analyzed to determine why the system had failed. This encoder system was found to have slipped off the crankshaft, resulting in the need for a new encoder mount system. A new encoder mount was designed and installed on a Detroit Diesel 3-53 engine. The encoder mount was designed to ensure positive contact with the crankshaft while not allowing the mechanism to have the same type of failure that was determined. During the validation of the encoder, the push rod connected to the fuel injector rocker arm failed, preventing further validation of the system. The failure of the push rods is described.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF FIGURES

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF TABLES

THIS PAGE INTENTIONALLY LEFT BLANK

I. INTRODUCTION

A. BACKGROUND

Diesel engines have many uses in both the military and civilian applications. They are used in powering trucks, automobiles, boats, and locomotives, as well as providing power for pumps, generators, compressors and many other machines. The U.S. Navy uses Diesel engines for propulsion on certain surface ships as well as on submarines for auxiliary power production. While these applications of Diesel engines require different power levels, Diesel engines work well in all of these situations for several reasons. Diesel engines have good low fuel consumption that is relatively flat across the power range, diesel fuel is cheap, and Diesel engines have a lower cost per horsepower than gas turbine engines. Additionally, they have the ability to generate large amounts of torque at a relatively low fuel consumption rate. Additionally, Diesel engines have a long life due to the rugged design of Diesel engines.

The Marine Propulsion Laboratory has a Detroit Diesel 3-53 engine on a waterbrake dynamometer to demonstrate the operation and characteristics of Diesel engines. This laboratory is used to conduct research on condition based maintenance (CBM). Additionally, students can take classroom knowledge and apply it to actual reciprocating engines and see how the classroom theory corresponds to engines in operation. For this engine setup to be successful, a vast array of sensors must be installed on the engine. When work began on this particular engine, several problems were discovered with the engine. These included mechanical problems, instrumentation problems, and problems with the encoder design. These problems will be discussed later.

The Diesel engine is equipped with many other measurement devices. While the engine has an array of sensors, the two main sensors are the optical encoder and the pressure transducers. These devices allow a user to gather information of the engine at a particular loading and speed. The pressure transducers have high frequency response so they can measure the pressure variation in one revolution. The optical encoder is a device that measures the angular position of the crankshaft.

The optical encoder mount has two parts. The first part is a device that is rigidly attached to the crankshaft. The second part is the equipment that mounts to the engine block. The encoder is connected to the mount by a coupling device that minimizes the noise transferred to the encoder through normal Diesel engine operation. The encoder mount has undergone many design iterations. The first encoder mount failed to provide adequate support for the encoder bearings [Ref. 1]. The second encoder mount was essentially an aluminum plate mounted on the end of three cantilevered beams. This designed was inadequate because it was determined that the optical encoder mount was moving approximately ± 0.02 degrees with respect to the engine block which would result in large errors when coupled with the encoder [Ref. 2]. Hudson designed and installed the current encoder mounting system.

While the encoder system that Hudson designed and installed had worked for a few years, the encoder began to give signals that did not make physical sense. Upon further investigation of the system, it became apparent that the current mounting system had failed. The screws that Hudson used to attach the encoder mount to the crankshaft had backed out during engine operation and began to scar the engine block mounting. After inspecting the encoder mount and crankshaft, it became apparent that a new design was needed that would not have these same faults.

B. OBJECTIVES

The objectives of this thesis are:

1. Determine why the previous encoder mount failed.

2. Design a new encoder mount that will ensure positive contact with the crankshaft at variable speeds and torques.

3. Demonstrate the engine operation and validation of the new encoder as well as discuss engine faults.

4. Calibrate the engine and associated software to establish a standard for future tests.

C. ORGANIZATION

Chapter II describes the engine, dynamometer, instrumentation, and data acquisition process.

Chapter III presents the failure analysis, design, manufacture, and installation of the sew encoder mount.

Chapter IV presents the procedure used to validate the design and briefly discuss the failure of the push rods.

Chapter V contains a summary and conclusion from this work.

THIS PAGE INTENTIONALLY LEFT BLANK

II. EXPERIMENTAL SETUP

A. EQUIPMENT

1. Diesel Engine

The engine used for this research is a Detroit Diesel Series 53 engine model 5033-5001N, as shown in Figure 1. It is a two stroke engine set in an inline configuration. This engine was originally installed in an U. S. Army 1-1/4 ton 6x6 Cargo Truck, commonly known as the “Gamma Goat.” The engine characteristics are given in Table 1.

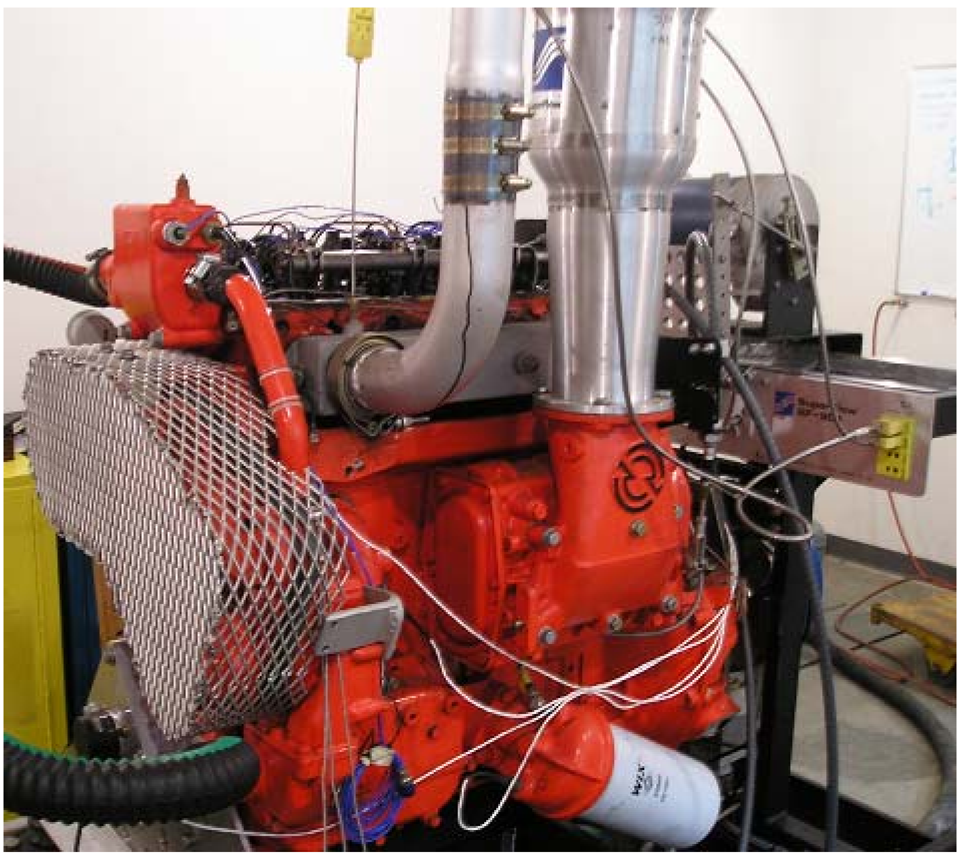


Figure 1. Engine Test Stand

Table 1. Engine Characteristics [Ref. 3]

Model	5033-5001N
Number of Cylinders	3
Bore and Stroke	2.875 x 4.5 in
Cylinder Displacement	53 cubic in
Engine Displacement	159 cubic in
Compression Ratio	21.0 : 1
Engine Type	Inline, 2 Stroke
Firing Order	1-3-2; Clockwise Rotation
Maximum Torque	198 foot pounds @ 1,500 RPM
Maximum Power Output	92 bhp
Maximum Power Speed	2,800 RPM
Engine Oil Capacity	12.5 qt (filter included)
Exhaust Valves per Cylinder	4

The air is supplied to the engine through a roots blower which supplies air at a positive crankcase pressure which is proportional to engine speed [Ref 4].

2. Dynamometer Test Stand

This engine is mounted on a SuperFlow 901 Engine Dynamometer test stand. The dynamometer uses a water break to absorb the power generated from the engine. This particular dynamometer has a maximum capacity of 1,000 hp and 10,000 rpm [Ref. 3.]

The Superflow Engine Cycle Analyzer (ECA) is a PC based data acquisition system. The sensor system collects the engine load signal from the dynamometer, crank angle and TDC signal from the optical encoder, and pressure signals from each of the pressure transducers mounted in each cylinder. This information is sent to a data acquisition computer, which processes and stores the data. During the data acquisition process, the ECA was used to record and store the pressure data from each of the three cylinders. The ECA has the ability to monitor 1 to 999 revolutions of data from the engine and store the ensemble average of this data to memory [Ref. 4].

B. OPTICAL ENCODER

Top Dead Center (TDC) is the reference value for angular position of the crankshaft. TDC is found when the volume in the cylinder is at the lowest point. To achieve TDC and combine that with the optical encoder, mechanical TDC must first be found in a cylinder. Cylinder one was chosen for this purpose because it is the first

cylinder to fire in the series and the ease of accessing the cylinder. To achieve mechanical TDC, a pry bar was attached to the flywheel and rotated the crankshaft until the cylinder head reached a maximum height. After mechanical TDC was found, installing the encoder with the new encoder mount was a simple procedure. This procedure can be found in Appendix C.

The optical encoder is a critical piece of equipment. It measures the angular position of the crankshaft in relationship to the number one cylinder. Since the other two cylinders are related to the first cylinder, the encoder also determines the position of the other two cylinders. The optical encoder used was a Heidenhain incremental Rotary Encoder [Ref. 5] with 720 counts per revolution, giving an angular resolution of 0.5°. The encoder provides a transistor-transistor logic (TTL) signal once per revolution, resulting in a measurement of TDC. This signal is sent to the data acquisition computer and allows for a reference which all other angular measurements are compared against. The pressures are recorded in each cylinder when the optical encoder triggers the data acquisition system.

The optical encoder is bolted to the engine frame closest to the number one cylinder. The optical encoder housing is made of 2 plates of aluminum and uses three 3/8 inch bolts to secure the housing to the engine block. This design is similar to the previous iterations, but the previous designs had three aluminum plates in the engine block mount. Since the new design fit with only two plates, less vibration would be picked up by the optical encoder. Additionally, the optical encoder mount is fit with a coupling that damped out the radial and axial vibrations that had damaged previous encoders. This coupling device can be seen in Figure 2, and the entire optical encoder mount can be seen in Figure 3.

Figure 2. Coupling Device

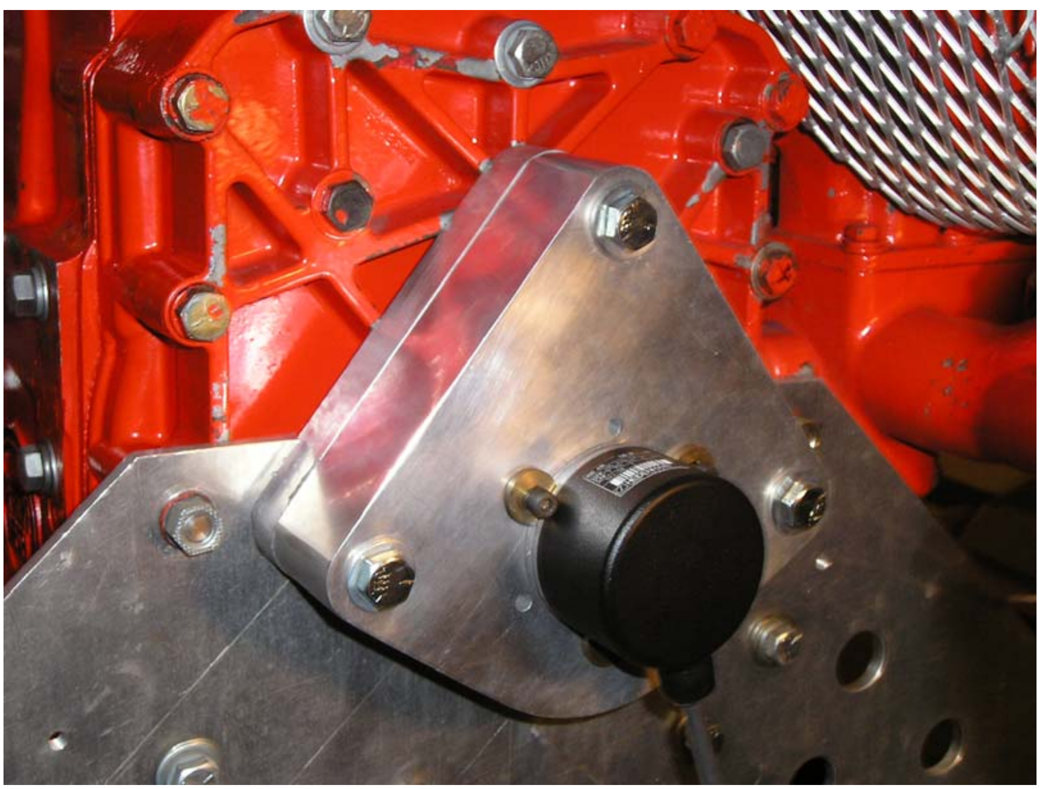


Figure 3. New Optical Encoder Mount

III. ENCODER MOUNT DESIGN

A. FAILURE ANALYSIS

The previous encoder design stopped providing accurate phase timing triggering, recording accurate readings for TDC, and failed to give accurate signals for the crankshaft angle. In order to determine why the encoder was giving faulty signals, the encoder mount had to be disassembled and analyzed. The previous encoder mount was removed by first loosening the flexible coupling from the optical encoder. This was conducted by taking an allan wrench and a light and loosening the coupling from underneath the encoder mount where there is a window just for that purpose. The next step was to remove the retaining bolts on the engine block mount with an allan wrench and physically removing the optical encoder. After the flexible coupling and encoder mount were exposed, the engine block mount had to be taken off. The engine block mount is made of three pieces of aluminum with varying thickness and it is attached to the engine with three bolts. These bolts were removed and the engine block mount was inspected. Deep scarring and aluminum shavings were noticed in one of the three aluminum plates. After the flexible coupling was separated from the encoder mount with the use of an allan wrench, the encoder mount was detached by removing the set screws and sliding the encoder mount off.

After all the parts were taken off, a thorough failure analysis of the system was the next step in determining why the encoder was sending faulty signals to the data acquisition computer. Since one possible source of failure was with the optical encoder, a new male connector was soldered with new pins and tested. This new receiver worked the same as the old one, so this was ruled out being a source of the failure.

Since the encoder wiring was correct, the logical step was to examine the hardware and see if the problem could be located. After examining the encoder mount and set screws along with the scarred aluminum plate, it became clear that the set screws had to have backed out during the engine operation. This forced the set screws into the aluminum plate, resulting in the scarring of the plate. Since the aluminum plate with the defects was located directly over the location of the set screws, this explained why the

encoder was relaying faulty signals to the data acquisition computer. The encoder mount had failed to keep positive contact with the crankshaft, resulting in slippage between the encoder mount and the crankshaft.

B. DESIGN OF NEW ENCODER MOUNT

Since it was now understood why this encoder mounting system failed, it became necessary to design a new system that would not experience this type of fault or any of the other faults that had been experienced in previous design iterations. While parts of Hudson's design failed, the basic idea of using the flexible coupling and set screws to attach it to the crankshaft remained in the new design. The major changes to the design would be to drill into the crankshaft and use a collar to keep the set screws from backing out.

The set screws used in this design are 1/4 inch with 28 threads per inch with a cone point. They are 1/2 inch long. This point of the set screw is what actually makes positive contact with the crankshaft and prevents any slippage in the encoder mount. A drawing of the set screws can be seen in Figure 4.

Since the previous design failed because the set screws did not provide enough contact against the crankshaft, the new design would fix this problem by drilling into the crankshaft using a 0.25" drill piece. The crankshaft would have to be drilled as deep as the set screws would penetrate the crankshaft until the shoulder of the set screw would rest against the crankshaft instead of just the point making contact with the crankshaft. In order to ensure that the crankshaft would be drilled at the correct locations, it was necessary to design a jig that would attach to the crankshaft and provide the locations where the crankshaft was going to be drilled. Figure 5 shows the machined part, while the machine drawings can be seen in Appendix B.

The jig was designed to rest against the back of the crankshaft seal and held in place by a bolt. It was designed to be a clearance fit over the crankshaft, with three 0.25" holes, 120° apart. The dimension chosen for the distance of the holes was set so the drill would be able to fit in the space allotted. These holes would be the guide for the drill bit so the holes would be drilled in the correct spot in the crankshaft.

The encoder mount was designed similarly to Hudson's design. However, since the total thickness of encoder mounting system was constrained by the diameter of the engine block mount opening, the diameter of the encoder mount had to be smaller because a collar was going to slide over the set screws. Additionally, the extension where the flexible coupling attaches had to be at least 0.5" long. Since the jig had three 0.25" holes 120° apart, the encoder mount had to have the same parts. This would be a clearance fit, with the same dimensions as the jig. A picture of the after it has been installed on the crankshaft can be seen in Figure 6, and the machine drawings can be seen in Appendix B.

The collar was designed to slip over the encoder mount with three slots cut out at 120° apart. The slots stopped where the set screws were designed to come in, so the set screws would be able to slide into the slots and would hold the collar in place. It was necessary to ensure that the back of the collar did not rest on the crankshaft seal so the data acquisition would not be altered by outside sources. The collar can be seen in Figure 7, and the machine drawings are included in Appendix B.

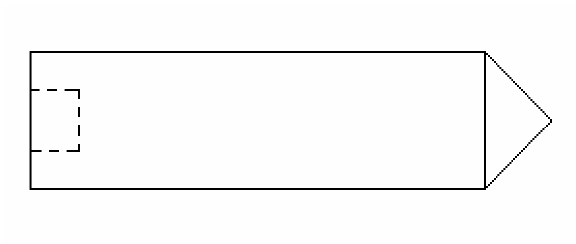


Figure 4. Drawing of Set Screw

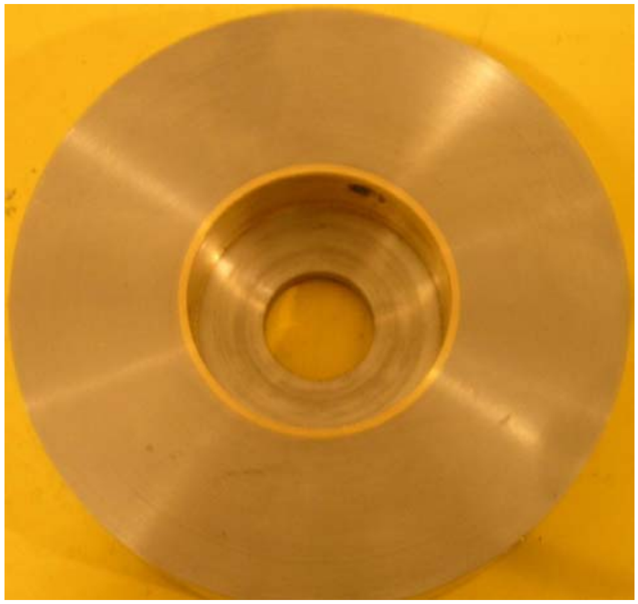


Figure 5. Picture of jig used to guide drill into crankshaft

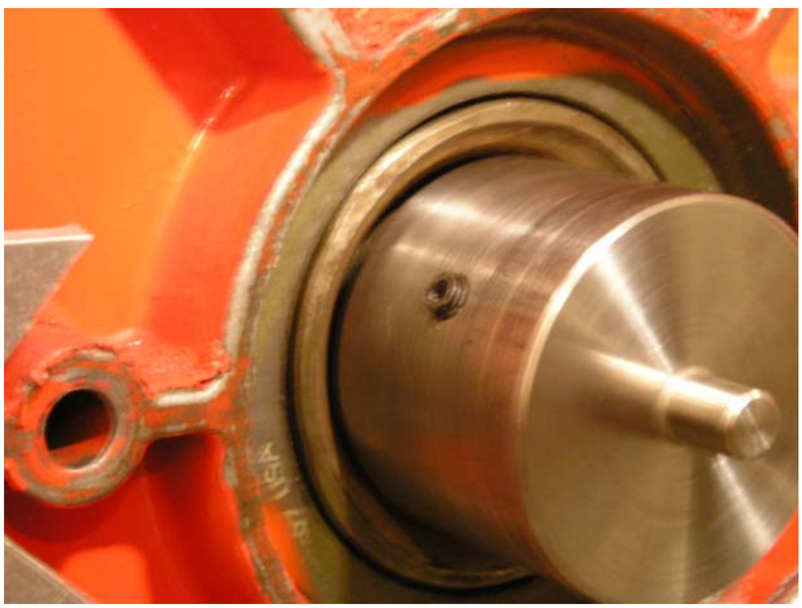


Figure 6. New encoder mount.
Note set screw installed and clearance between
crankshaft seal and encoder mount

Figure 7. Picture of Collar.
Note the depth of the slots.

C. INSTALLATION

After the parts were manufactured, the parts had to be installed before the new system could be verified experimentally. After bolting the jig onto the crankshaft, drilling the holes, and removing the crankshaft, the three holes were found to be drilled to the proper depth. The installation of the encoder mount was next. Since there is very little clearance between the crankshaft and the mount, the encoder mount has to be arranged perpendicular to the crankshaft to facilitate installation. After the encoder mount was in place, loc-tight was considered for the set screws but was deemed not necessary since the set screws were going to be physically unable to back out after the collar was installed. After the set screws were in place, the slots in the collar did not fit over the set screws. It turned out that the set screws were not designed to be machined to the degree of accuracy calculated, so they had to be filed down a few thousands of an inch before the collar slipped over the encoder mount. Figure 8 shows how the collar did not fit over the set screws, and Figure 9 shows the collar locked into place.

Figure 8. Installation of the collar over the encoder mount before the set screws were filed down

Figure 9. Encoder mount with collar installed after filing.

After installing the collar and encoder mount, the engine block mount had to be remounted. The procedure for this is the same as taking it off, with one exception. The previous design had three aluminum plates between the optical encoder and the encoder mount, but the new design only uses the two aluminum plates that were not scarred. Since the previous bolts that held the engine block mount in place were too long, new bolts were installed that held the engine block mount in place. Figure 10 shows the engine block mount, and Figure 11 demonstrates how the encoder mount and flexible coupling appear on the engine.

Figure 10. Picture of new engine block mount. Note the two plates and the window for tightening the flexible coupling at the bottom.

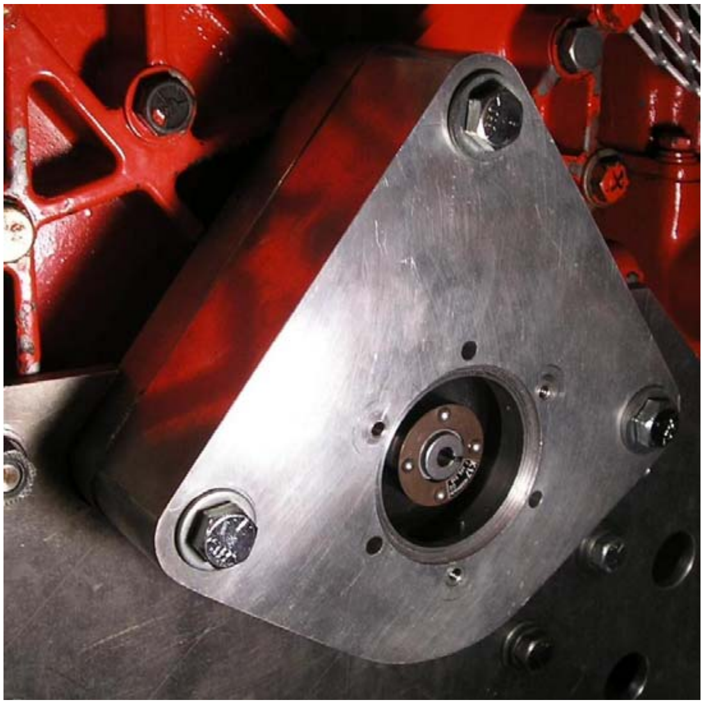


Figure 11. Engine Block Mount Installed over Encoder Mount.

IV. RESULTS

A. SETUP

To ensure that the encoder mount design, manufacture, and installation were satisfactory, a simple test run at 1450 RPM and 15 ft-lb of torque was conducted. These conditions were chosen because the engine had not been run in six months and a basic test was needed to make sure that the system worked with the new encoder mount and that the data acquisition computer still functioned. For these results, the 720 count encoder was used.

The Detroit Diesel 3-53 has 4 exhaust valves per cylinder. During operation, these four exhaust valves are depressed by the rocker arms and clear the cylinder of the burned mixture of fuel and air. All of the exhaust valves were timed according to the procedure found in the maintenance manual [Ref. 3].

The fuel injection system operates a little different than the exhaust valve system. The fuel injection is accomplished using direct mechanical injection of the fuel into the cylinder. The injector is controlled by the rocker arm acting on the injector. As the camshaft rotates, the rocker depresses on the plunger, spraying an atomized mist into the combustion chamber. The amount of fuel injected into the cylinder is metered by a fuel rack which is linked directly to the governor. The fuel control rack can be moved from maximum fuel to no fuel during normal operation.

In order to time the injectors properly, the injectors used are N50 with a timing dimension of 1.460 inches. The procedure set forth in the maintenance manual [Ref. 3] was followed with one exception. Instead of using the tool recommended by the manufacturer, a rod of 1.460 inches was manufactured and used to time the injector versus using the tool stated in the maintenance manual.

The following data will be used to validate the correct timing of the exhaust and fuel injector timing, as well as the encoder mounting system.

B. CYLINDER PRESSURE DATA

In order to validate the optical encoder system, a pressure versus volume plot was obtained after sampling and averaging the data for 11 cycles. The pressure versus crankshaft angle curve seen below, Figure 12, is typical of these plots.

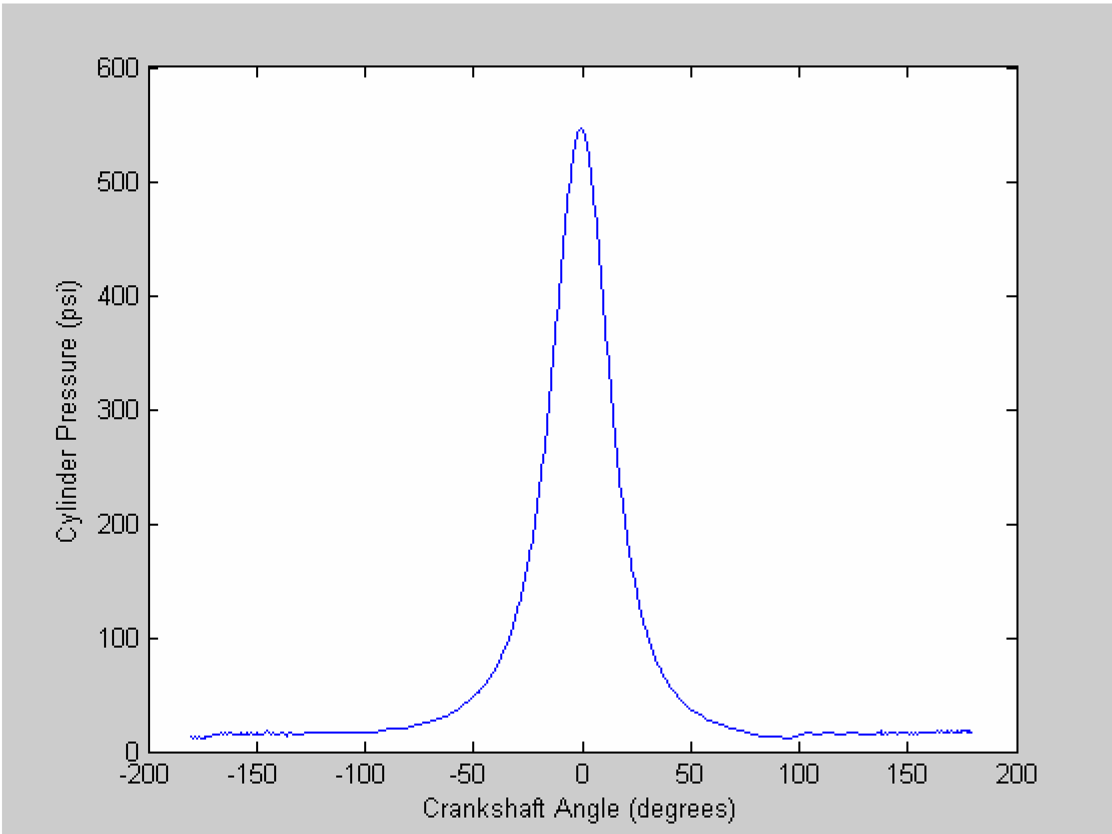


Figure 12. Pressure versus Crankshaft Angle

Since these data were averaged over 11 cycles, it verifies that the optical encoder system was not slipping and the data acquisition system was also functioning.

This plot shows some interesting features of the Diesel engine. Mechanically, the exhaust ports on cylinder number one open at 95°, which corresponds to the engine event timing [Ref 1]. At 95°, the exhaust ports open and the pressure drops to atmospheric pressure. See Figure 13. As the exhaust valves open, some of the outside air rushes through the exhaust valves and the mixture inside the cylinder is a mixture of burned air and fresh. The cylinder does not vent the mixture until 120° when the intake ports inside

the cylinder begin to expel the mixture in the cylinder with pressurized air from the roots blower. The plot below signifies that the exhaust valves were timed properly.

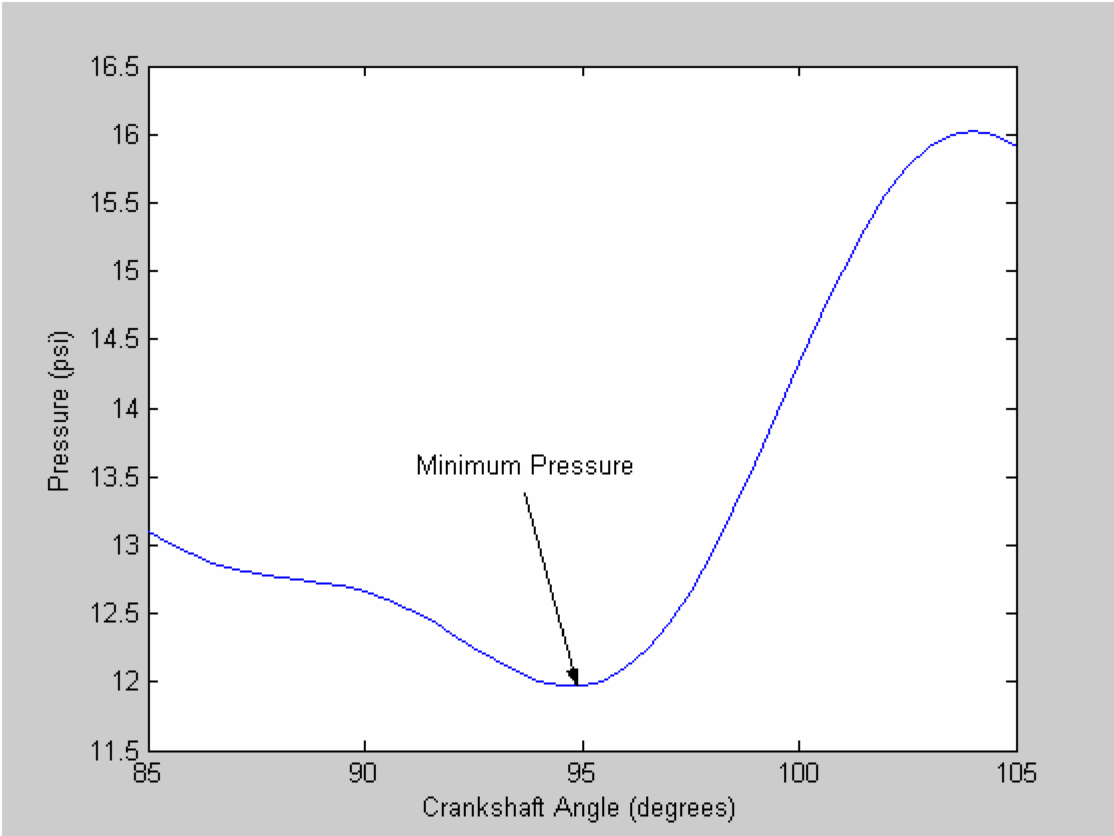


Figure 13. Timing of Exhaust Valve Verification

Figure 14 displays the pressure versus volume plot and Figure 15 shows the ideal diesel cycle.

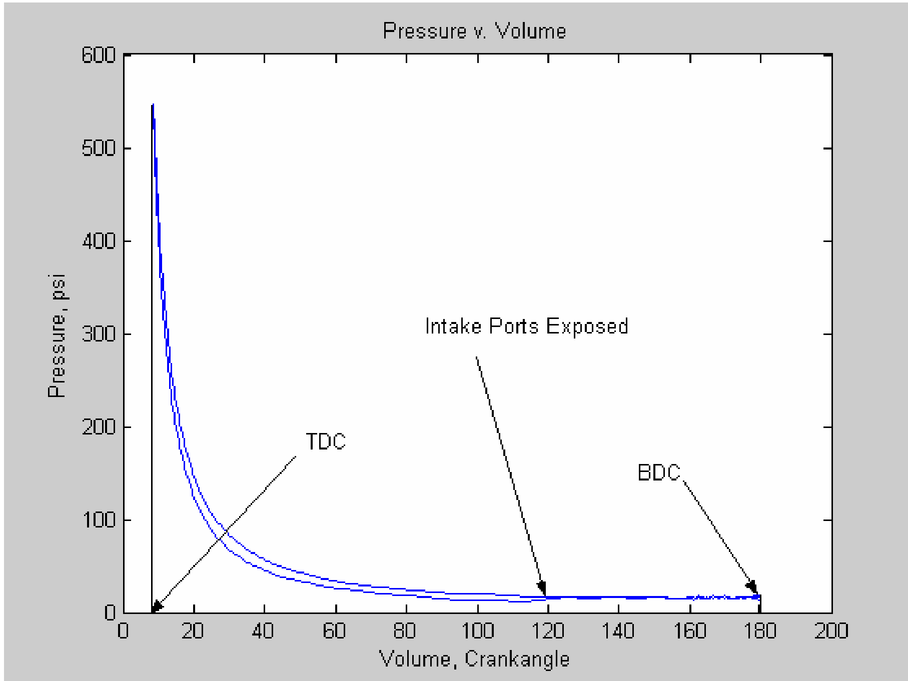


Figure 14. Pressure v. Volume

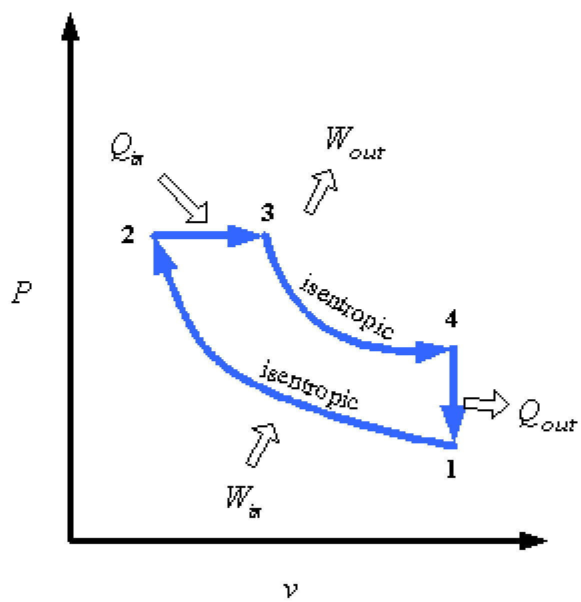


Figure 15. Ideal Diesel Cycle

These two plots have similar shape and characteristics. Comparing the two graphs, it is seen that station 1 occurs at 120° when the intake ports are exposed. From 1 to 2, as the piston travels up the cylinder, the volume decreases, increasing the pressure adiabatically. Just prior to TDC, fuel is mechanically injected into the cylinder, and the

mixture burns. This mixture burns at a constant pressure, and moves along to station 3. From there to 4, the expansion of the gas drives the piston to 4, providing the work necessary to drive the crankshaft. In the test engine, the entire diesel cycle happens from -120° to 120°.

To validate the fuel injector timing, a similar procedure was done that was done to validate the exhaust valve timing. When the fuel injectors are timed properly, the peak cylinder pressure should occur 3 to 6 crankshaft degrees after TDC [Ref. 5]. However, according to Figure 16, the maximum cylinder pressure happens at -0.5°. While this data was not analyzed at the time, this figure shows that there is a problem with the procedure used for timing the fuel injectors.

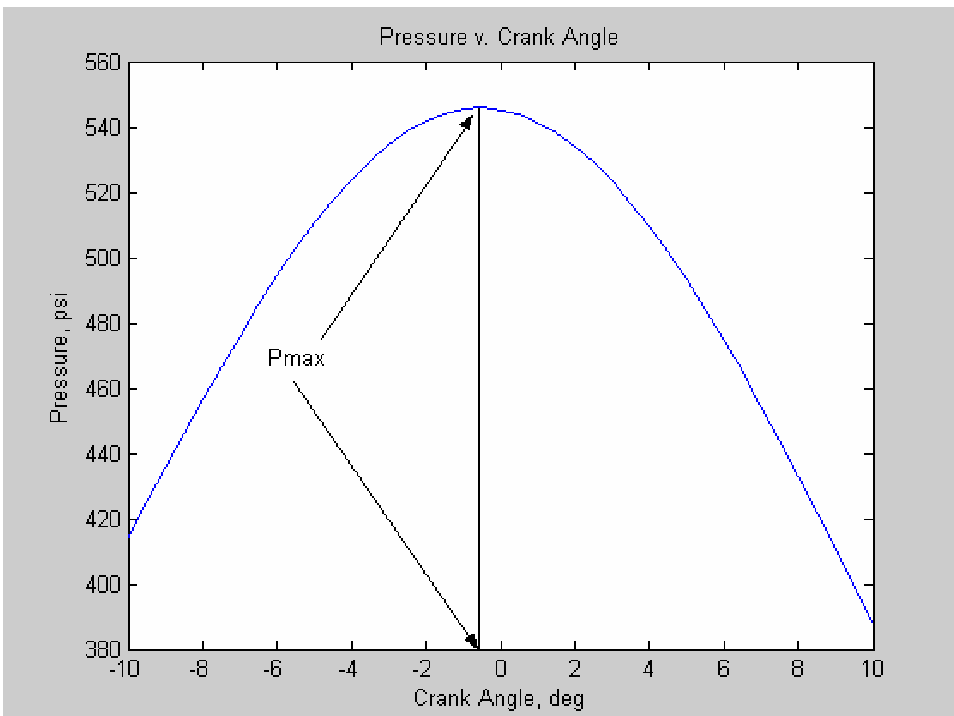


Figure 16. Pressure v. Crank Angle

Since the maximum pressure occurred a before TDC, the injectors are timed improperly and indicate a problem with the procedure used for timing the injectors. According to Armstrong [Ref. 5], improper timing of the fuel injectors results in a lower peak pressure and a lower efficiency of the engine. Therefore these injectors need to be retimed.

However, before these data could be analyzed and the injector timing could be verified, a major engine catastrophe occurred. The push rods controlling the rocker arms for the injectors on cylinder two and three failed and sheared off. Therefore, no more data could be taken since the fuel injectors on the number two and three cylinders would not inject any more fuel into the combustion chamber. Figure 17 shows the shearing of the push rod.

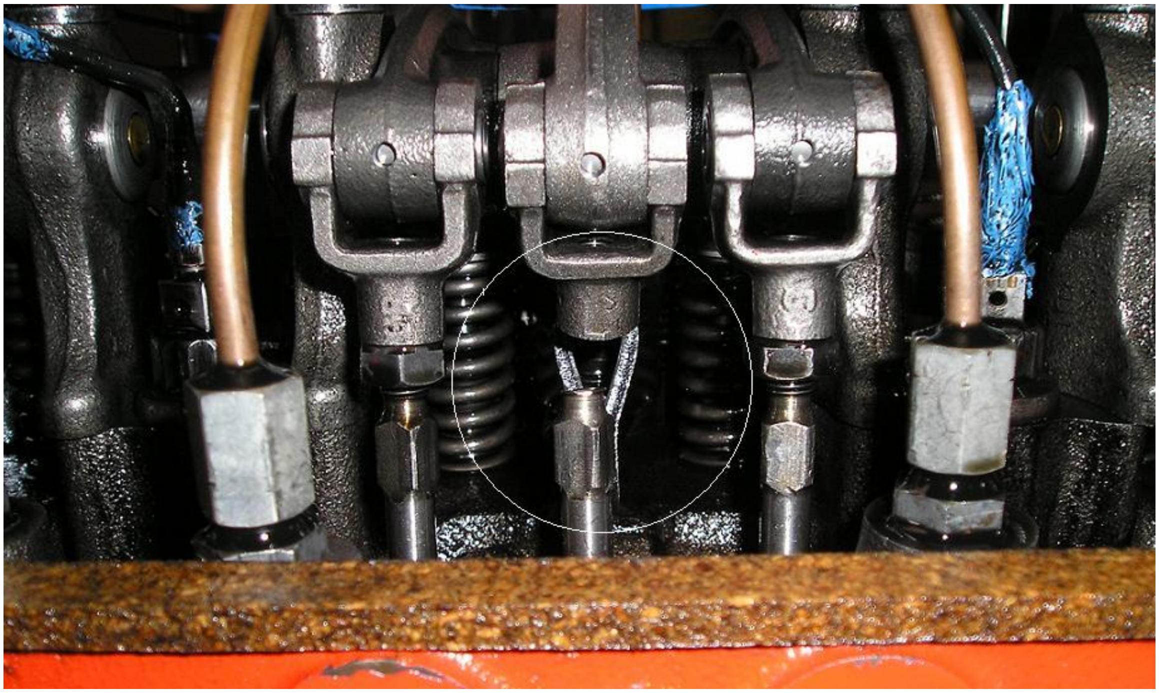


Figure 17. Failure of Push Rod

The failure of the push rod was first seen on the data acquisition computer, when the pressure versus volume diagram did not show any work being done by the engine. Additionally, the engine did not respond quickly to the throttle, which led to the examination of the push rods. However, there is no data available demonstrating the failure of the push rods.

After the failure of the push rod, no further data were available for the engine. However, it is valuable to note that when the maximum pressure occurs before TDC, there are problems with the injectors and maintenance is necessary to prevent failure of either the fuel injectors or rocker arm assembly. Additionally, since maximum pressure occurs before TDC, the performance and efficiency of the machine is lower than ideal.

V. SUMMARY AND CONCLUSIONS

A. SUMMARY

A three cylinder, two stroke Detroit Diesel 3-53 diesel engine was equipped with a new encoder mount that correctly measured TDC and angular position with 0.5 degrees of resolution. After the new encoder mount system was installed on the engine and engine maintenance done, a simple test run was done to verify the optical encoder mount. After verifying the exhaust valve timing, a separate fuel injector timing test was done and it was found that the fuel injectors were timed improperly. Before engine maintenance could be conducted on the fuel injector timing, the push rods on the fuel injectors failed on the second and third cylinder.

B. CONCLUSIONS

The failure of the previous encoder system was caused by the set screws backing out from the encoder mount. This caused the scarring that was seen on the aluminum mounting plate. Since this design had fundamental problems, a new encoder mount was designed that utilized positive contact between the set screws and crankshaft. Additionally, a collar was placed over the set screws to prevent them from backing out and scarring the aluminum plate. These steps will prevent this failure from happening in the future.

The encoder system was validated by averaging 11 cycles of data taken with the new encoder system. The engine was tested at 1450 RPM and 15 ft-lb of torque. The results from the data showed that the encoder is validated because the encoder did not slip and the data acquisition computer recorded the individual pressures and crankshaft position. After analyzing the data, the new optical encoder mount was able to predict a future engine failure. Since the maximum pressure was recorded before TDC, this signified that the fuel injectors were timed incorrectly. Before any preventative maintenance could be done on the engine, the push rod controlling the fuel injector failed, resulting in a major engine catastrophe. Since the push rod did fail, new push rods must be installed before the fuel injectors can be retimed properly.

THIS PAGE INTENTIONALLY LEFT BLANK

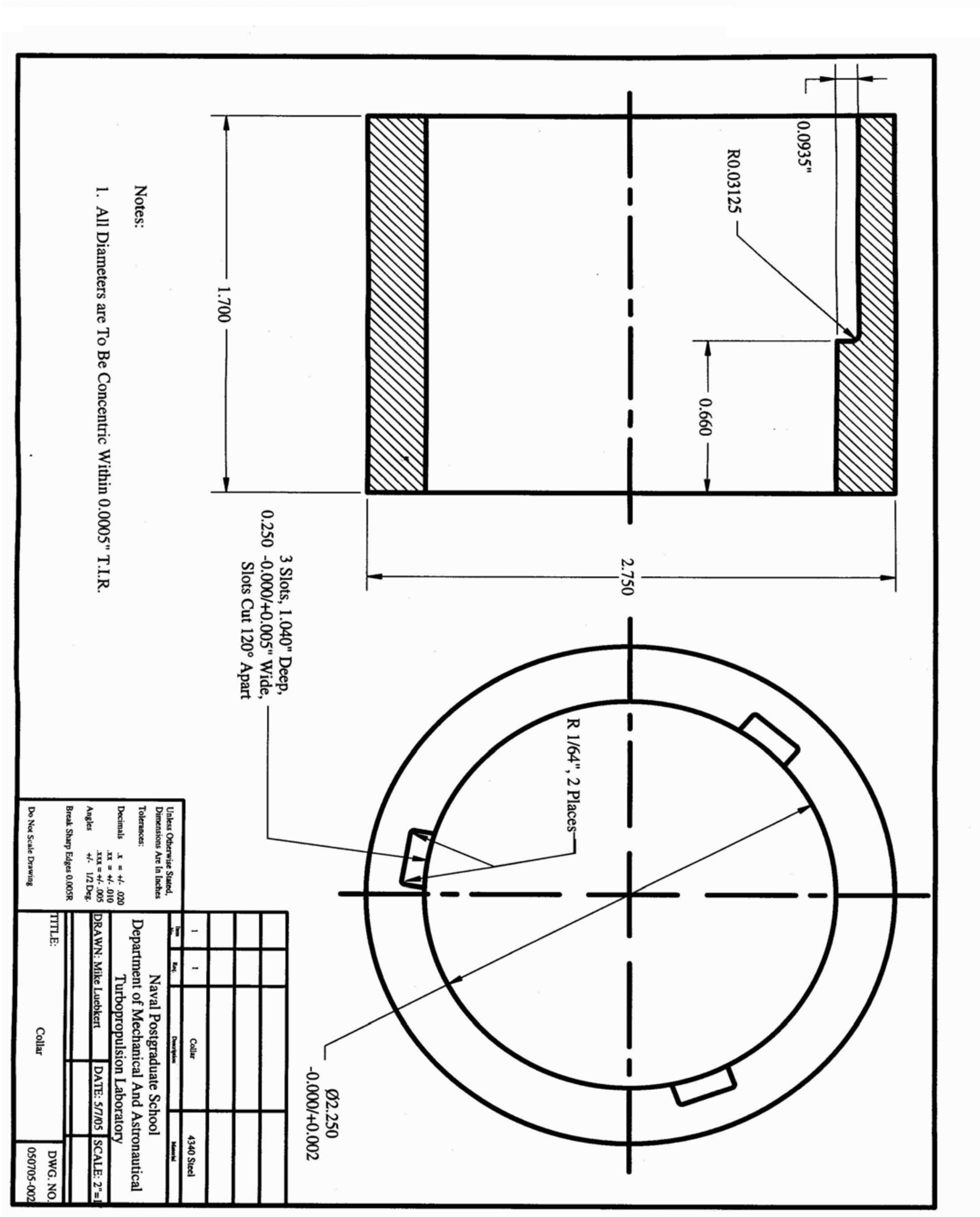
APPENDIX A: ENGINE MAINTENANCE

1. One of the flywheel bolts sheared off during the reinstallation of the flywheel.
   Solution: The fatigued bolt was removed, and six new SAE Grade 8 bolts with new lock washers were installed and torqued to 45 foot-pounds.
2. The previous fuel flow meter was not working properly.
   Solution: A new turbine flow meter was installed, but it has not been verified due to the push rod failure.
3. Engine maintenance had not been done in years.
   Solution: New primary and secondary fuel filters were installed on the engine. Additionally, the engine oil was replaced with 10W-40 oil and a new oil filter was installed.
4. The engine exhaust valves were not timed properly.
   Solution: Using a feeler gauge, all four exhaust valves on all three cylinders were timed properly.
5. The installed fuel injectors were not timed properly.
   Solution: Using a manufactured timing device, the fuel injectors were timed according to the injectors installed. However, after the push rods on two of the injectors snapped, it was discovered that incorrect fuel injectors were installed on the engine. Correct fuel injectors have been ordered and are awaiting installation.

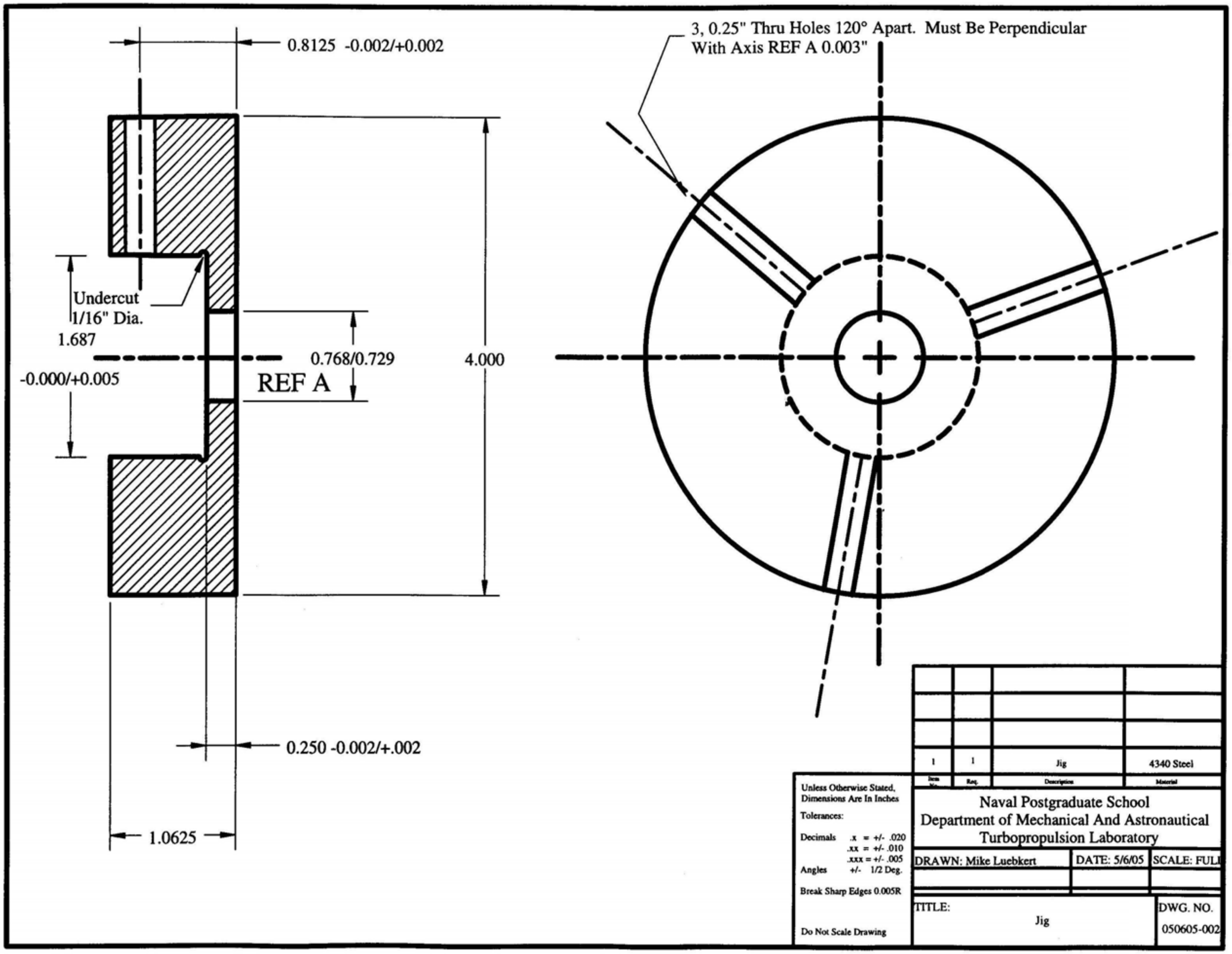
THIS PAGE INTENTIONALLY LEFT BLANK

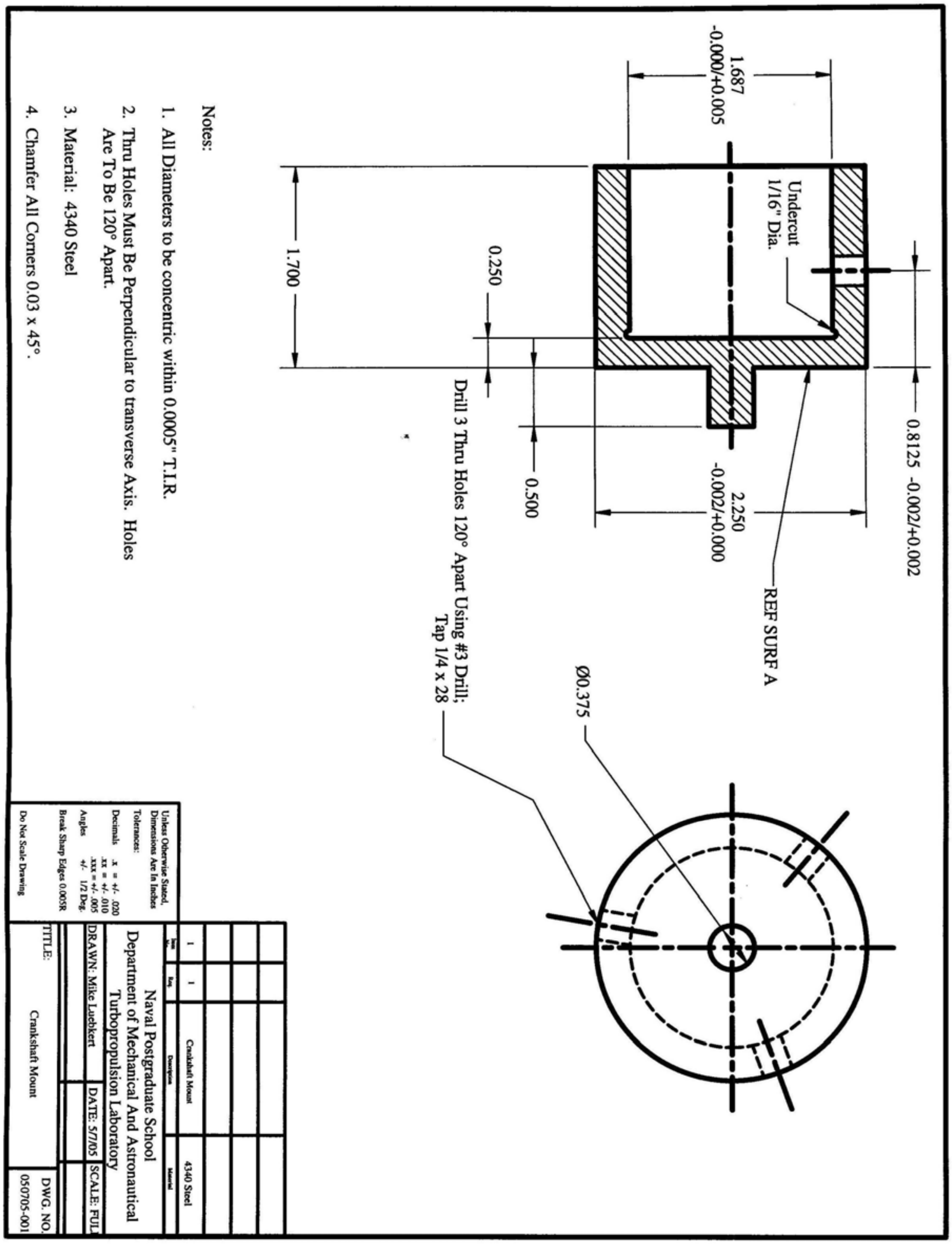
APPENDIX B: MACHINE DRAWINGS OF OPTICAL ENCODER MOUNT

This appendix contains the technical drawings for the crankshaft mount for the optical encoder, the jig used to drill holes into the crankshaft for the set screws, and the collar. This new design was an iteration on a previous design with some major design changes. All drawings were prepared using TurboCad v6 [Ref. 6].



0.0935"
R0.03125
0.660
1.700
2.750
Notes:
1. All Diameters are To Be Concentric Within 0.0005" T.I.R.
3 Slots, 1.040" Deep,
0.250 -0.000/+0.005" Wide,
Slots Cut 120° Apart
R 1/64", 2 Places
Ø2.250
-0.000/+0.002
Unless Otherwise Stated, Dimensions Are In Inches
Tolerances:
Decimals .x = +/- .020
.xx = +/- .010
.xxx = +/- .005
Angles +/- 1/2 Deg.
Break Sharp Edges 0.005R
Do Not Scale Drawing
1
1
Collar
4340 Steel
Naval Postgraduate School
Department of Mechanical And Astronautical
Turbopropulsion Laboratory
DRAWN: Mike Luebkert
DATE: 5/7/05
SCALE: 2"=1
TITLE:
Collar
DWG. NO.
050705-002


0.8125 -0.002/+0.002
Undercut
1/16" Dia.
1.687
-0.000/+0.005
0.768/0.729
REF A
4.000
0.250 -0.002/+.002
1.0625
3, 0.25" Thru Holes 120° Apart. Must Be Perpendicular
With Axis REF A 0.003"
1
1
Jig
4340 Steel
Item No.
Req.
Description
Material
Unless Otherwise Stated, Dimensions Are In Inches
Tolerances:
Decimals .x = +/- .020
.xx = +/- .010
.xxx = +/- .005
Angles +/- 1/2 Deg.
Break Sharp Edges 0.005R
Do Not Scale Drawing
Naval Postgraduate School
Department of Mechanical And Astronautical
Turbopropulsion Laboratory
DRAWN: Mike Luebkert
DATE: 5/6/05
SCALE: FULL
TITLE:
Jig
DWG. NO.
050605-002


1.687
-0.000/+0.005
Undercut
1/16" Dia.
0.8125 -0.002/+0.002
2.250
-0.002/+0.000
REF SURF A
0.250
1.700
0.500
Drill 3 Thru Holes 120° Apart Using #3 Drill;
Tap 1/4 x 28
Ø0.375
Notes:
1. All Diameters to be concentric within 0.0005" T.I.R.
2. Thru Holes Must Be Perpendicular to transverse Axis. Holes Are To Be 120° Apart.
3. Material: 4340 Steel
4. Chamfer All Corners 0.03 x 45°.
Unless Otherwise Stated, Dimensions Are In Inches
Tolerances:
Decimals .x = +/- .020
.xx = +/- .010
.xxx = +/- .005
Angles +/- 1/2 Deg.
Break Sharp Edges 0.005R
Do Not Scale Drawing
Item No.
Req.
Description
Material
1
1
Crankshaft Mount
4340 Steel
Naval Postgraduate School
Department of Mechanical And Astronautical
Turbopropulsion Laboratory
DRAWN: Mike Luebkert
DATE: 5/7/05
SCALE: FULL
TITLE:
Crankshaft Mount
DWG. NO.
050705-001

APPENDIX C: ESTABLISHING TOP DEAD CENTER

In order to get accurate data, it is necessary to ensure that mechanical TDC is coupled with the optical encoder TDC signal. The following procedure details the steps necessary to align the optical encoder with the crankshaft after mechanical TDC of cylinder one has been established. The number one cylinder is the cylinder chosen for the reference.

1. After mechanical TDC of the number one cylinder is established using a pry bar, loosely attach the optical encoder to the mount using the three retaining bolts.
2. Attach the coupling to the optical encoder using an allen wrench. There is a window on the underside of the engine mount that allows for access. A mirror and flashlight may be necessary for this step.
3. Rotate the optical encoder until the TDC signal illuminates on the ECA sensor interface.
4. Carefully tighten the retaining bolts on the engine mount.

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF REFERENCES

1. Bell, J. E. "Assessment of Diesel Engine Condition Using Time Resolved Measurements and Signal Processing," Naval Postgraduate School, Monterey, CA, M. Sc. Thesis, September 1996.

2. Hudson, J. W. "Development and Calibration of a Torsional Engine Model for a Three-Dylinder, Two-Stroke Diesel Engine," Naval Postgraduate School, Monterey, CA, M. Sc. Thesis, December 1997.

3. Detroit Diesel Series 53 Service Manual, Detroit Diesel Corporation, May 1990.

4. Engine Cycle Analyzer Operators Manual, 1990, SuperFlow Corporation.

5. Incremental Rotary Encoders, Heidenhain Corporation, April 1997, pp. 18-19 and 32-33.

6. Armstrong, R. A., "Fault Assessment of a Diesel Engine Using Vibration Measurements and Advanced Signal Processing," Naval Postgraduate School, Monterey, CA, M. Sc. Thesis, December 1996.

7. IMSI. TurboCAD v6 (Version 6.5 Build 59.6) [Computer Software]. 1999.

THIS PAGE INTENTIONALLY LEFT BLANK

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
   Ft. Belvoir, VA

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, CA

3. Department Chairman, Code ME
   Department of Mechanical Engineering
   Naval Postgraduate School
   Monterey, CA

4. Professor Knox T. Millsaps, Jr., Code ME/MI
   Department of Mechanical Engineering
   Naval Postgraduate School
   Monterey, CA

5. Curricular Officer, Code 34
   Department of Mechanical Engineering
   Naval Postgraduate School
   Monterey, CA

6. ENS Michael R. Luebkert
   Midlothian, VA